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Critical Gap Analysis of Dual Lane Roundabouts

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Abstract

Roundabouts are increasingly popular because of their performance in terms of safety, capacity, and cost. Roundabouts have the potential to reduce accident risk since the traffic flows merge and diverge at small angles, and low speeds. Under certain conditions, roundabouts also improve the flow of traffic at the intersection, compared to other choices. In this paper we present a methodology for estimating an important input in the calculation of the capacity of roundabouts: the critical gap. The critical gap is the smallest gap that a driver is willing to accept to merge with the circulating traffic and mainly determines the gap acceptance behavior of the driver. The critical gap is not directly observable. Only gaps that drivers have accepted or rejected are observed. These gaps define upper and lower values for the underlying critical gap but not its exact value. The paper builds on previous literature proposing a rigorous statistical methodology for the estimation of the critical gap, and demonstrates its application through field measurements. It is assumed that the critical gap has a lognormal distribution among the driver population with a mean value that is a function of a number of explanatory variables. Based on these assumptions the critical gap and its distribution can then be estimated using maximum likelihood. A case study in a dual lane roundabout in Stockholm is used to illustrate the proposed methodology using video and other data. The results show that the critical gap depends, among other factors, on the target lane (near or far), the type of the vehicle. The results are also compared to values recommended by other studies.

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Keywords: Critical Gap, Roundabout, Capacity, Gap acceptance

1. Introduction

Roundabouts are channelized intersections where the traffic moves in circular way around the central island (O'Flaherty, 1997). Special characteristics of roundabouts include yield control for the approaches at the arms, channelization of movements, and geometric curvatures that ensure that the circulation traffic moves in relatively low speeds (FHWA, 2000).

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Roundabout capacity depends on a number of factors, including the total traffic flow rate from each approaching arm that can join the circulatory traffic during the analysis period, geometry, vehicle mix, and driver behavior. The focus of this paper is on the impact of driver behavior, in particular the gap acceptance behavior. Typically, the circulatory traffic has priority, while the approaching traffic has to stop and find an acceptable gap to enter the circulating flow. The minimum accepted gap (critical gap) is different from driver to driver, since each driver has its own considerations for safety, urgency, vehicle type, etc.

The objective of the paper is to present a maximum likelihood framework for the estimation of the critical gap in two-lane roundabouts. Hagring (2003) states that gap acceptance models can be classified as macro (interactions between traffic streams, geometric considerations) and micro (at the driver level). The approach adopted in this paper is based on micro analysis, using detailed data of vehicle behavior and trajectories at a specific two-lane roundabout. As such, the model is also useful for use in microscopic traffic simulation models to capture behavior at roundabout facilities.

The model can be estimated rigorously using detailed data of driving behaviour. The main challenge of estimating the critical gap is that it is a latent variable, not directly observed. Furthermore, the parameters of the distribution of the critical gap can be estimated as a function of various explanatory variables, such as speeds of approaching vehicles, location, time waiting for a gap to appear, vehicle type, etc.

2. Background

Due to the importance of gap-acceptance and its impact on the capacity of roundabouts, a large number of studies have been conducted. Miller (1972) introduced rigorous approaches for the estimation of critical gaps. Brilon et al (1999) give a comprehensive survey of the different methods and their development over time. They also evaluate a number of the proposed methods according to criteria such as distributional assumptions, consistency, robustness, and compatibility to capacity models.

Earlier efforts for modeling gap acceptance, in general, were based on the distribution of the critical gap (defined as the unobservable minimum gap a driver is willing to accept in order to merge) with no attempt to explain the underlying behavior - see, for example, Herman and Weiss (1961), Miller (1972). Hewitt (1983) proposed a method to estimate the distribution of the critical gaps for drivers who rejected the first gap (lag) they encountered upon arrival at the intersection. Under the assumption that each driver's critical lag and critical gap are equal, the probability distribution of critical times is estimated.

A number of later efforts focused on more behavioral models, which incorporate factors that explain the critical gap, as opposed to simple distributions. Daganzo (1981) used a probit model to estimate the parameters of a normal distribution of critical gaps at intersections and to capture the heterogeneity of driver behavior. This approach accounted for within driver variation, as well as across driver variation. Mahmassani and Sheffi (1981) also used a probit model to estimate the mean and the variance of critical gaps at unsignalised intersections, and concluded that the effect of the number of gaps rejected on the critical gap was significant. Cassidy et al. (1995) developed a discrete choice framework to model the gap acceptance behavior at a stop controlled T-intersection. They found that a gap acceptance function with appropriate explanatory variables has significantly more predictive power than a function that includes only the mean gap length.

Ahmed et. al. (1996) as part of their lane change model, proposed a gap acceptance model for freeway traffic, that is appropriate for moving vehicles that attempt to change lanes. The model explicitly recognizes that for merging into an adjacent lane, both the lead and lag gaps must be acceptable. Drivers are expected to be more aggressive under mandatory lane changing situations compared to discretionary lane changing situations. The proposed model captures this behavior by allowing different parameters for the gap acceptance model under the two situations.

For the estimation of the parameters of the models a number of methods have been employed (depending on the structure of the underlying model). However, for many modeling approaches the maximum likelihood estimation provides a lot of advantages and robustness. Brilon et. al. (1999) in their survey of different methods, indicate that maximum likelihood-based methods gave superior results. Maximum likelihood methods in the context of critical gap have also been studied in detail in Troutbeck (1992) and Tian et. al. (1999).

An important underlying assumption for the various methods is the distribution of the critical gap. Troutbeck (1992) assumed a lognormal distribution, while Brilon (1995) used a hyper-Erlang with similar results. It has been

reported (Brilon et. al., 1999) that the lognormal distribution has been found to be consistent with empirical observations and results in average values that are representative of average driver behavior.

Finally, regarding critical gaps at roundabouts, a number of studies have been conducted but focused mainly on one lane intersections. The study of two lane roundabouts is more limited. Golias (1981) used maximum likelihood methods (applying the EM algorithm) to estimate the critical gap in T-intersections with two major streams. Hagring (2000a) estimated, using maximum likelihood, critical gaps for each stream, when more than one streams are involved. He concluded that critical gaps are different for the two streams, and this can have significant impact on the capacity for the minor approaches. The critical gaps were found to be smaller in the far lanes. Hagring (200b) reports that the difference is in the order of 0.2 to 0.3 seconds. This also provided the basis for the recommendations by CAPCAL, a version of the Swedish Highway Capacity Manual, where the critical gap is a function of the geometric characteristics of the roundabout, and the location of the corresponding lane (outer, inner):

$$t_c = 4.904 + \frac{0.090}{q} - 0.52w_l + 0.56 * (N_l - 1) + 1.1 * (P_{HV} - 0.061) \quad (1)$$

Where:

t_c = the critical gap

w_l = the length of weaving area

N_l = lane location (outer lane =1, inner lane =2)

q = volume (veh/sec)

P_{HV} = proportion of heavy vehicles

As a result the critical gaps differ between the movements.

3. Formulation

The critical gap is assumed to follow the lognormal distribution, and be a function of a number of factors such as, vehicle type, impatience, etc. As such the model is formulated as:

$$G_n^{cr(t)} = e^{(X_n(t) \cdot \beta + \epsilon_n(t))} \quad (2)$$

where,

$G_n^{cr(t)}$ = critical gap for driver (n) at time t

$X_n(t)$ = vector of explanatory variables

β = coefficients to be estimated

$\epsilon_n(t)$ = random error term

The error term $\epsilon_n(t)$ is assumed to follow the normal distribution, $\epsilon_n \sim N(0, \sigma_\epsilon^2)$. This is consistent with the assumption that the critical gap has a lognormal distribution, as suggested in previous studies (Brilon et al, 1999). Under this assumption, the probability that a gap at time t , G_m , is acceptable by driver n , is given by:

$$\begin{aligned} \Pr(G_m \text{ acceptable}) &= \Pr(G_m > G_n^{cr(t)}) \\ &= \Pr(G_m > \exp(\beta X_n(t) + \epsilon_m)) \\ &= \Pr(\ln(G_m) > \beta X_n(t) + \epsilon_m) \\ &= \Pr(\epsilon_m < \ln(G_m) - \beta X_n(t)) \\ &= \Phi\left(\frac{\ln(G_m) - \beta X_m}{\sigma_\epsilon}\right) \end{aligned} \quad (3)$$

where,

G_m : gap that has been evaluated by driver n ,

$G_n^{cr(t)}$: critical gap for driver n at time t

β : parameters to be estimated

X_n : vector of explanatory variables associated with driver n .

$\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution.

Assuming that driver's decisions related to accepting or rejecting gaps are observed, we denote the sequence of observations for a given driver n , as follows:

$$(D_{1n}, D_{2n}, \dots, D_{in}, \dots, D_{T_n n})$$

Then the log-likelihood function can be formulated as:

$$L = \sum_{n=1}^N \ln P(D_{1n}, D_{2n}, D_{3n}, \dots, D_{T_n n}) \quad (4)$$

where,

$$P(D_{1n}, D_{2n}, D_{3n}, \dots, D_{T_n n}) = \prod_{t=1}^{T_n} P(D_{tn}) = \prod_{t=1}^{T_n-1} P(\text{gap } i \text{ is rejected}) P(\text{gap } T_n \text{ is accepted}) \quad (5)$$

$$P(D_{1n}, D_{2n}, D_{3n}, \dots, D_{T_n n}) = \prod_{t=1}^{T_n-1} \Phi\left(\frac{\ln(G_n(t)) - X_n(t)\beta}{\sigma_\epsilon}\right) * \left(1 - \Phi\left(\frac{\ln(G_n(T_n)) - X_n(T_n)\beta}{\sigma_\epsilon}\right)\right) \quad (6)$$

Subscript n refers to a driver and subscript t ($1, 2, \dots, T_n$) indicates the sequence of gap events driver n faced. The formulation is quite general and allows the extension of the model to a number of directions, including the incorporation of error terms that capture the heterogeneity among drivers (see for example, Ahmed et al 1996).

4. Case Study

A two-lane roundabout, Brommaplan, in Stockholm was used to apply the methodology described in the previous sections. Brommaplan is a one of the entry and exit points from and to Stockholm center. It is a large roundabout with six approaching arms. The roundabout is very congested during the morning and evening peak periods. The data collection involved vehicle counts, speed measurements, and video recording of the operations of the intersection for the period from 7:30 am to 11:30 am. Figure 1 illustrates the intersection and the data collection arrangements.

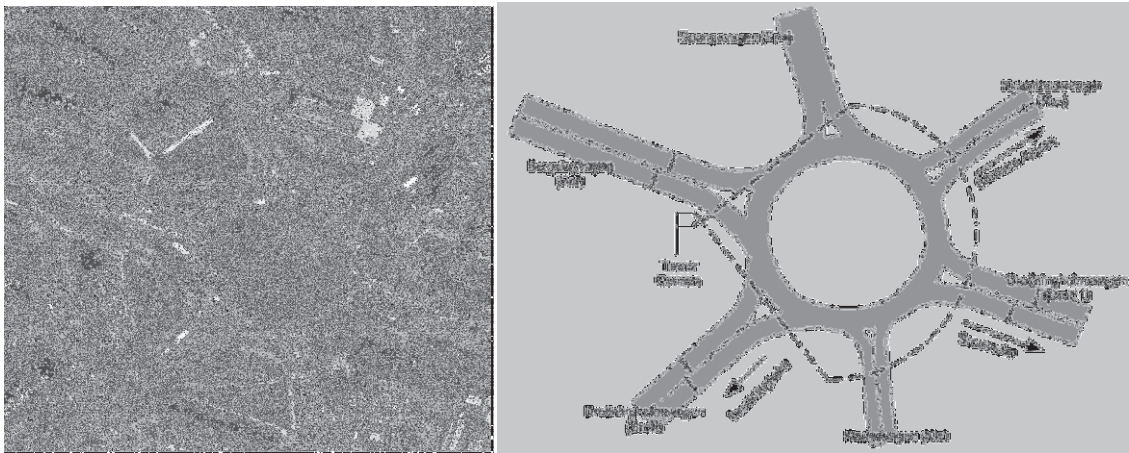


Figure 1. Roundabout and data collection configuration

The raw data, in particular the video data, was processed to extract useful information such as, type of vehicle in the minor stream (subject vehicle) and the major stream (circulating vehicle), the gap event for each lane, delay in the yielding point, speed of the subject vehicles, lane destination, time stamps for the various events, delay, queuing conditions that develop, time to cross the conflict area, etc.

Tian (1999) defines gap events as the time events marking the beginning and the end of each major stream gap. In the processing of the data, a gap event was associated with the arrival of a driver in the minor stream at the yielding point. Drivers in that stream have lower priority and hence, seek gaps in streams with higher priority. Gap event data and associated information were extracted from the video recording. The time spent waiting for a gap (delay) was also measured as the time the subject vehicle waits at the yielding point to join the major traffic, until it merges.

The processing of the data was focused on behavior in the inner lane and outer lane separately, since the assumption of the model is that that drivers merging from the inner lane have to accept the gap in the near and far lane. Figure 2 illustrates the terminology used in the remaining of the paper (consistent with Hagring, 2000).

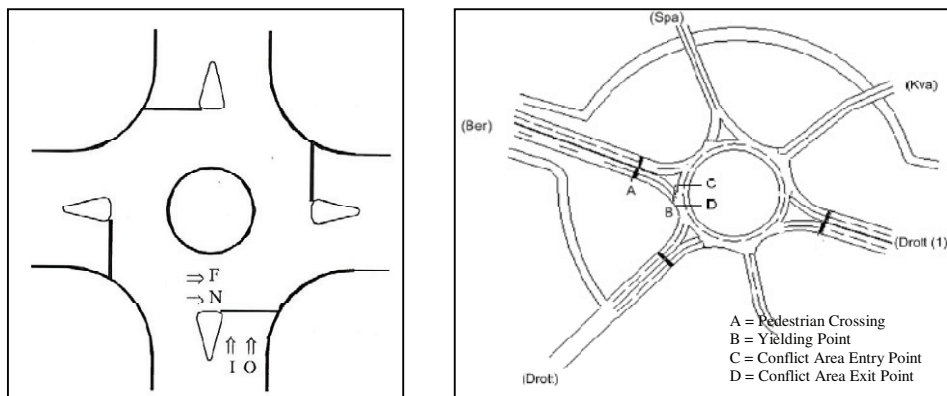


Figure 2 Terminology of lane location in roundabouts (source: Hagring, 2000b) and data collection points

The gap event measurements start at the time when a driver in the minor traffic arrives at the yielding point. The driver observes several gap events before merging into the major or circulatory traffic. The gap in the major traffic is measured at the point where the traffic enters and exits from the conflict area (Figure 2, points B and C respectively). We assume that the entering point is near the inner lane merging area and the exit line is located after the outer lane merging area. The data analysis included recording of the arrival time at B and exit time at D, as well as flows in the major traffic lanes at locations C and D. In Figure 2, following Hagring (2000a), F and N indicate the far and near major traffic lanes (circulating), while I and O indicate the inner and outer approaching, minor lanes respectively. It is assumed that the critical gaps associated with traffic in lanes F and N are not the same (similar to the simultaneous model of Hagring, 2000). The events of interest in this paper are the combinations of (Inner lane (I) with Far (F)) and (Outer Lane (O) with Near lane (N)).

Figure 3 illustrates an example of a sequence of 4 gaps with respect to a vehicle in the outer lane (a) and the inner minor lane (b). n indicates the gap in the near (major) lane and f the gap in the major far lane.

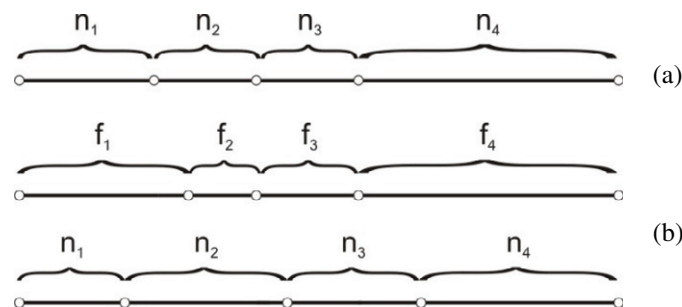


Figure 3 Observed gap events at the major traffic; (a) outer Lane, (b) inner Lane

The outer lane driver waits at the yielding point and observes the gap event sequence resulting from the near lane. The sequence consists of gap events (n_1, n_2, n_3, n_4). The driver rejects three gaps and accepts the last one. On the other hand, the inner lane driver faces seven pair of gaps. He/she rejects six pairs and accepts one pair of gap events (n_4, f_4). Table 1 summarizes the sequence faced by each driver, depending on their location.

Table 1. Gap event sequence for the outer and inner lane drivers

Approaching Lane							Decision
<i>gap</i>	<i>Outer Lane</i>		<i>Inner Lane</i>				
1	n1	Rejected	n1	Rejected	f1		Accepted
2	n2	Rejected	n2	Accepted	f2		Rejected
3	n3	Rejected	n3	Rejected	f3		Rejected
4	n4	Accepted	n4	Accepted	f4		Accepted

The data set that was used for the estimation of the model included 53 drivers in the inner lane and 95 drivers in the outer lane. The outer lane model is simpler, compared to the inner lane model. It is not affected by the far lane traffic circulatory movement. On the other hand, the inner lane movement is more complicated since drivers in that lane evaluate the gap events on both, the near and far lanes. A number of explanatory variables were used to develop a set of models capturing the critical gap for the different target movements. The set of variables included standard variables, such as vehicle type, traffic conditions, speeds, length of queue, delay, fist gap characterization:

Vehicle type (subject and conflicting) = $\begin{cases} 1 \text{ if Light Vehicle (Car, MPV and Van)} \\ 0 \text{ if Heavy Vehicle (Truck and Bus)} \end{cases}$

First gap = $\begin{cases} 1 \text{ if gap is the first gap the driver is facing} \\ 0 \text{ otherwise} \end{cases}$

Delay = time spent waiting for an acceptable gap. It is also an indicator that drivers may become impatient as the time passes by and therefore become more aggressive

Travel time in conflict area = time spent traveling through the conflict area of the intersection. It serves as a proxy for the degree of congestion in the area and the prevailing speeds.

Queue length = the length of the queue when the vehicle, from the minor stream, arrived at the intersection.

Queue order = $\begin{cases} 1 \text{ if vehicle is the second (first) in the queue} \\ 0 \text{ otherwise} \end{cases}$
The variable attempts to capture effects where, a vehicle second in the queue follows the leader, taking the opportunity to merge, although the available gap would not be acceptable under other conditions.

Speeds = speeds of individual vehicles approaching the merging point from the circulating lanes (main lanes)

Speeds were measured at entry, circulatory and exit points. The speed measurement locations are shown in Figure 3. There are four measurement points. The speed distribution for the circulating traffic is also shown.

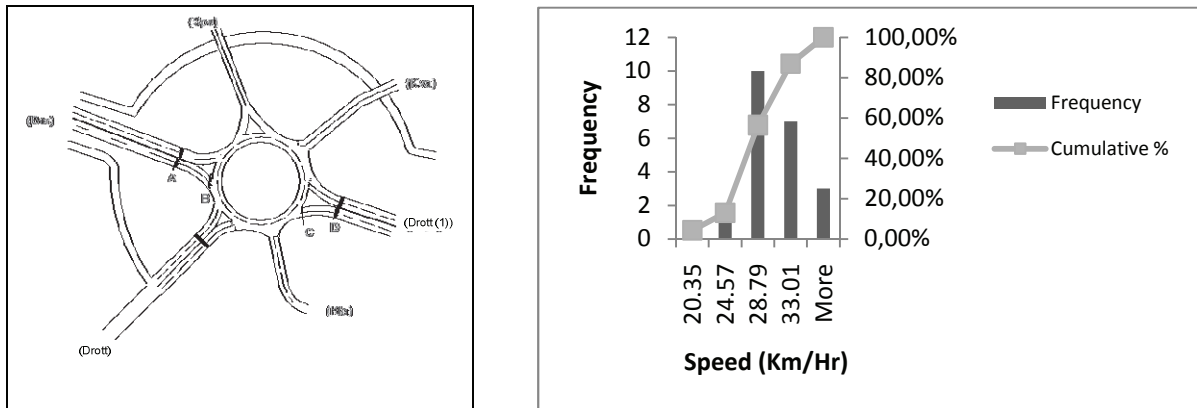


Figure 3. The Speed measurement joints and speed distribution of circulating traffic.

A number of different specifications were tested. In many cases the estimation results did not fulfill the a-priori expectations for some of the variables. Table 2 summarizes the main estimation results for one of the models.

Table 2. Parameter estimation results (t-statistic values in parentheses)

Variable	Inner Lane				Outer Lane	
	Far		Near			
Constant	1.227	(1.745)	1.3675	(1.933)	1.233	(1.767)
Subject vehicle type	-0.300	(-0.492)	0.4504	(0.643)	0.511	(0.835)
Circulating vehicle type	0.081	(1.217)			-0.492	(-1.149)
Travel time in conflict area			-0.1320	(-1.665)		
No. of observations	194				175	
LL (β)	-174.295				-79.226	
LL (θ)	-342.147				-162.111	
Mc Fadden ρ	0.490				0.513	

The main observation is that the critical gap is affected by the vehicle type. Both, the inner and outer lane results indicate similar behavior with respect to the interactions with the near lane. In particular, light vehicles, merging from the inner lane to the far lane have smaller critical gaps than heavy vehicles. Clearly the longer length of the heavy vehicles impacts the value of the critical gap they can accept. On the other hand light vehicles, merging to the near lane from the inner lane, have longer critical gaps compared to heavy vehicles, possibly due to the fact that heavy vehicles in this particular maneuver (characterized by smoother operating angles) may be more aggressive and at the same time more intimidating to approaching circulating flow. This impact is also consistent in the case of merging from the outer lane. In that case visibility considerations may also play a role, as the view of heavy vehicles on the outer lane, maybe be less impacted by the presence of a vehicle in the inner lane. The impact of circulating vehicles is also mixed, and in some respects counter-intuitive. Light circulating vehicles increase the critical gap of vehicles merging into the far lane from the inner lane, while they reduce the critical gap for vehicles merging from the outer lane. It should be noted that the percentage of the heavy vehicles in the sample is relatively small and hence the vehicle type variables may capture other effects as well (e.g. speed).

Travel time in the conflict area is used to capture the overall level of congestion in the roundabout, as shorter travel times mean higher overall speeds in the area. The variable has a negative sign indicating that drivers accept smaller critical gaps when conditions in the intersection are congested.

Table 3 compares the values of the average critical gaps from the estimated model to results from other studies. The estimated critical gap for the outer lane movements and the inner-far lane merging is similar to the other references. However, the critical gap for the inner-near lane merging, estimated by this study is lower than other studies. In fact, the critical gap for the inner-near lane merging is much lower than the critical gap from the near-far movement (also compared to other studies). This seems to be consistent with a-priori expectations however, as it is

much easier for drivers to perceive the safe gaps for the former movement, than when merging to the far lane. Other studies though (for example Hagring, 2003 and 2000b) show much smaller difference.

Table 3. Comparison of average critical gap values (sec) for various studies

Approach	Destination lane	Proposed model	Hagring (2003)	Hagring (2000)	CAPCAL
Outer Lane	Near	3.29	3.68	4.27	4.38
Inner lane	Near	3.58	4.64	4.62	4.86
	Far	4.37	4.68	4.40	4.04

Table 4 summarizes results assessing the impact of vehicle type, for different vehicle type interactions. Light vehicle drivers are more conservative since they accept larger gaps compared to heavy vehicle drivers. The table also illustrates that the inner lane drivers seem to be more careful to cross the traffic in the near lane. Although the number of near lane traffic is smaller than the far lane traffic, the inner lane drivers still wait for larger gaps, in order to merge directly into the far lane (to avoid stopping into the middle of circulatory traffic and interfering with the near lane movement, creating queues in the circulatory traffic).

Table 4. Impact of vehicle type on critical gap (sec)

Type of Vehicle		Type of Movement		
		Inner		Outer
Subject	Object	Near	Far	Near
Light	Light	4.33	3.58	3.78
Light	Heavy	4.19	3.54	6.03
Heavy	Light	2.82	4.21	2.19
Heavy	Heavy	-	-	3.52

5. Conclusion

Estimating critical gaps in unsignalized intersections is a difficult task due to the fact that they are not directly observed. The paper presented a maximum-likelihood formulation of the problem, based on previous research on the topic. The model was used to estimate critical gaps at one busy roundabout in Stockholm. The results, in many aspects, are consistent with previous findings. They also highlight the importance of a number of explanatory variables. In addition, they indicate that the difference between the critical gap among drivers aiming at merging into the far lane (from the inner lane) and the critical gap for merging into the near lane is much higher compared to what was previously reported in the literature. Further testing of the model is needed, with more extensive data sets, to verify the results presented in this paper.

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